He, Congrong & Morawska, Lidia (2003) ***Relationship between indoor/outdoor concentrations of particles : a critical review***. In: Proceedings of 7th International Conference Healthy Buildings, 7-11 December 2003, National University of Singapore, Singapore.

Relationship between indoor/outdoor concentrations of particles: a critical review

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ABSTRACT
The relationship between indoor and outdoor concentration levels of particles in the absence and in the presence of indoor sources has been attracting an increasing level of attention. Understanding of the relationship and the mechanisms driving it, as well as the ability to quantify it, are of importance for assessment of source contribution, assessment of human exposure and for control and management of particles. It became particularly important to address this topic when evidence came from epidemiological studies on the close association between outdoor concentration levels of particles and health effects, yet with many studies showing that indoor concentrations could be significantly higher than those outdoors. This paper presents a summary of an extensive literature review on this topic conducted with an aim to identify general trends in relation to the I/O relationship emerging from studies conducted worldwide. The review considered separately a larger body of papers published on PM_{10}, $PM_{2.5}$, as well as the smaller database on particle number and number or volume size distribution. A specific focus of this paper is on naturally ventilated houses. The conclusion from the review is that despite the multiplicity of factors that play role in affecting the relationship, there are clear trends emerging in relation to the I/O relationship for particle mass concentration, enabling more general predictions to be made about the relationship. However, more research is still needed on particle number concentration and size distribution.

INDEX TERMS
Indoor/outdoor relationship; Particle number concentration; Naturally ventilated houses

INTRODUCTION
There are many factors affecting particle concentrations in indoor and outdoor environments and the resulting I/O concentration ratios. It is often a challenging task to identify contributions of individual factors to the concentrations and their ratios measured indoors. For naturally ventilated houses the main factors include: indoor source strength, penetration of outdoor particles indoor, deposition rate and air exchange rate. For mechanically ventilated houses, in addition to the above, the main factors are the type and efficiency of the filters used as well as the operating parameters of the HVAC system.

When no indoor sources operate for suitably long periods and thus no particles are generated from indoor sources, the particle indoor (C_{in}) to outdoor (C_{out}) concentration ratio can be expressed as (Koutrakis *et al.*, 1992):

$$\frac{C_{\text{in}}}{C_{\text{out}}} = \frac{Pa}{a+k} \tag{1}$$

where P is penetration factor, a is air exchange rate (h^{-1}) and k is the decay rate due to diffusion and sedimentation. Particle concentrations can be expressed as number of particles or mass per unit volume of air. Despite the simple form of Eqn (1), determination of the I/O

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ratio with a reasonable accuracy using this equation is only rarely possible, as only rarely are all three parameters on the right-hand side of the equation known for a particular indoor environment. In the presence of operating indoor sources the relationship between indoor and outdoor concentrations becomes more complicated as it also includes emission rates of all indoor sources. Therefore an assessment of this ratio without measurements is an even more challenging task. Yet, knowledge of this ratio is of importance for risk assessment, for evaluation of the relative role of indoor and outdoor sources to the overall risk, and for identification of the best mitigation strategies for the environment in question.

This review was undertaken with an aim to identify any existing trends in relation to I/O ratios. Such trends could be used as a general guide to the likely values of the ratio in situations when the parameters determining the ratio for a particular environment are not known and in the absence of experimental data for the ratio. This paper reports on the trends identified for naturally ventilated houses for two scenarios: no indoor particle sources operating, and indoor sources operating.

I/O PARTICLE CONCENTRATION RATIOS IN THE ABSENCE OF OPERATING INDOOR SOURCES

PM_{10} and $PM_{2.5}$

Most of the data reported on I/O ratios is for PM_{10} and $PM_{2.5}$ mass size fractions and has become available from studies conducted in Europe, Asia, USA and Australia. A variety of methods have been used for determination of particle mass concentration including: gravimetric method of particle collection on a filter (e.g. Monn *et al.*, 1997), TEOM (with or without a seasonal-specific correction factor for loss of semi-volatile material due to the heating of the sample filter) (e.g. Long *et al.*, 2001), annular denuder system (e.g. Lee *et al.*, 1997) or TSI DustTrak (using a light scattering technique where the amount of scattered light is proportional to the volume concentration of the aerosol) (e.g. Morawska *et al.*, 2001). Figure 1 is a compilation of the results reported in the literature on I/O ratios of PM_{10}. Indicted also in Figure 1 is a median value for PM_{10} I/O ratio, which for all the studies reviewed is 0.70.

For $PM_{2.5}$ ratio a median value is 0.91 and the range of the reported values is somewhat larger than for PM_{10} and extends from 0.54 to 1.08. A higher ratio is expected for $PM_{2.5}$ compared to PM_{10}, since penetration factor for larger particles in the supermicrometre range is lower than for smaller particles in this range, and also the deposition loss rate of these larger particles is higher. The most important conclusion, which can be drawn from inspection of Figure 1 is that despite the differences between the indoor environments investigated (which were in terms of penetration factor, deposition rate and air exchange rate) the contribution of outdoor air as a source of indoor particles is pretty consistent across all the studies.

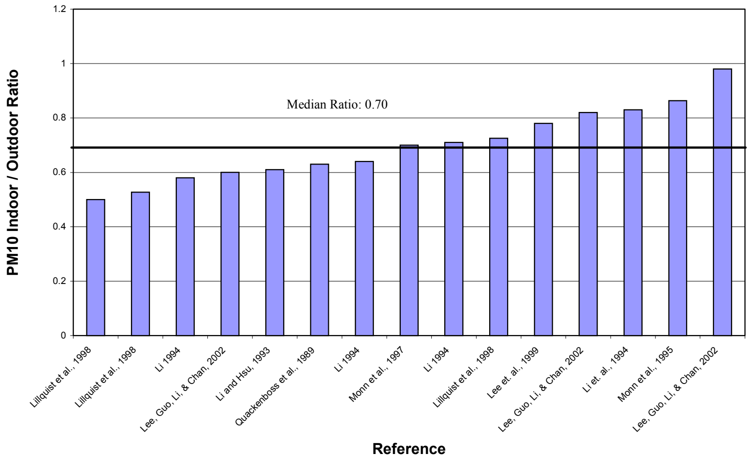

Figure 1 Summary of the reported data on I/O PM_{10} ratio in the absence of operating indoor sources. This figure is modified from Morawska and He (2003).

Volume or Number Size Distribution

More recent studies have been employing real time (or near real time) measurement methods, usually with the capability for particle size classification and for particle number measurements. The instruments most commonly employed for such studies are scanning mobility particle sizer and aerodynamic mobility particle sizer for the smaller and larger particles, respectively. While the instruments measure particle number, the data from studies using the instruments has been analysed either in terms of particle number concentration or in terms volume concentration ($\mu m^3/cm^3$) calculated from the number values. Figure 2 is a compilation of results presented by four studies, which reported I/O ratios in the absence of operating indoor sources for different size fractions.

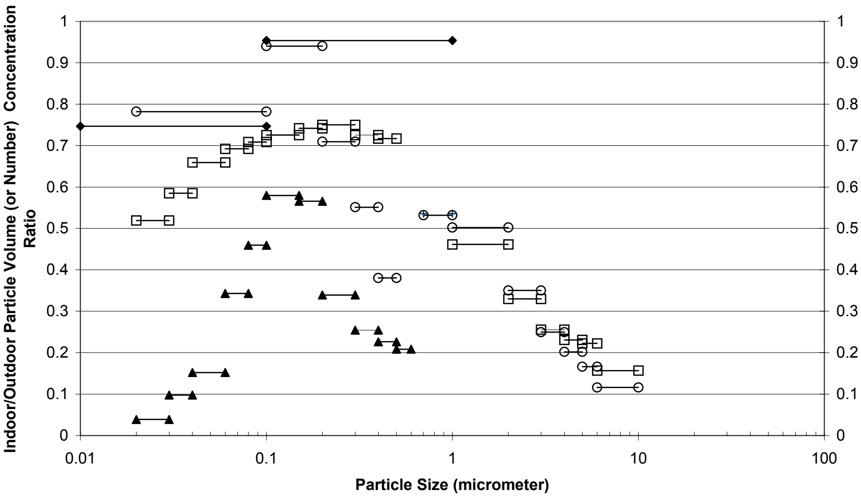

Figure 2 Summary of the reported data on I/O particle number concentration (triangles, diamonds), and volume calculated from number (squares, circles) in the absence of operating indoor particle sources. ▲—Li *et al.* (1993); ♦—Frnack *et al.* (2003); □—Long *et al.* (2001); ○—Abt *et al.* (2000b).

It should be kept in mind that each of the studies used either different instruments or investigated different size ranges, or presented the results in a different format. Figure 3 presents the results obtained from measurements of indoor and outdoor particle number size distribution in two residential houses in Brisbane, Australia, using the same instruments in both houses, conducted by the authors of this paper. It can be seen that there are major differences between I/O ratios, particularly for larger particles for the two houses. A general conclusion, from inspection of the results presented in Figures 2 and 3, is that the scatter of the reported results for size-classified particles is substantial, making it difficult to identify any trends.

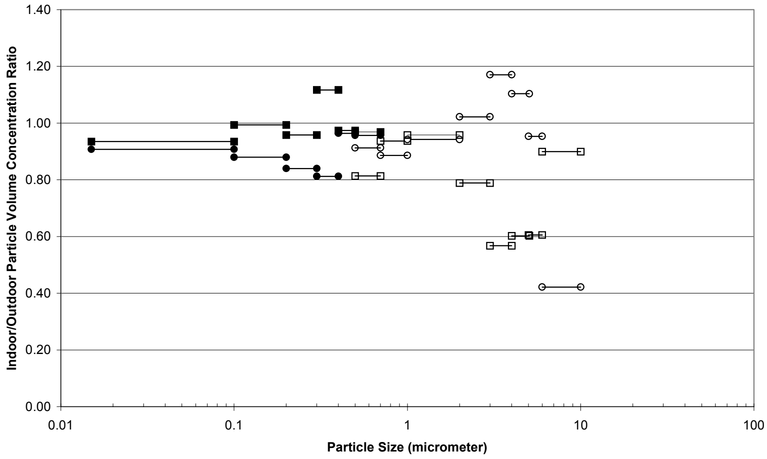

Figure 3 I/O ratio of particle number size distribution measured in two residential houses in Brisbane, Australia.

I/O PARTICLE CONCENTRATION RATIOS IN THE PRESENCE OF OPERATING INDOOR SOURCES

Contribution of indoor sources to indoor particle concentration levels depends in the first instance on the characteristics of the sources, particularly their strength, but of equal importance are the operating parameters of the building, particularly the air exchange rate. Most of the studies reviewed concluded that the highest impact was from smoking, cooking and general activities. Many of the studies, however, while stating that the measurements were conducted in the presence of operating sources, did not analyse the contribution or the effect of the individual sources. Some studies reported particle concentrations only in terms of average values, particularly if the measurement techniques used were based on gravimetric sample collection. Other studies reported average concentrations as well as short-term variation. From these it can be seen that short term increases in particle concentration as a result of source operation, could be up to two orders of magnitude above the average values.

PM_{10} and $PM_{2.5}$

The results from the studies, which investigated I/O ratios of PM_{10} concentrations in naturally ventilated buildings in the presence of operating indoor sources, are compiled in Figure 4. It can be seen from Figure 4 that the median from all reported studies is 1.47. For $PM_{2.5}$ the range has been from 1.00 to 2.40 with a median value of 1.21. As expected, almost all these values are above one and are higher than the values for the cases when no indoor source operated. The spread of the values is also much higher than in the absence of indoor sources. However, despite the differences in the environments investigated, differences in air exchange rates and the dominant impact of different sources in these environments, most of the reported values of I/O ratios are below two, with only a few significantly above this value.

Volume or Number Size Distribution

Due to the differences in instrumentation used, studies on particle number concentration tend to employ somewhat different experimental designs than studies on indoor particle mass characteristics. In particular, instrumentation for particle number or size distribution measurements enables collection of real time data; therefore, there has been a tendency to include more investigations on short-term variation in particle concentration, time series analyses as well as the investigations of the impact of individual sources. Figure 5 presents a compilation of results reported from four studies investigating particle size distribution (number size distribution measured, volume size distribution calculated).

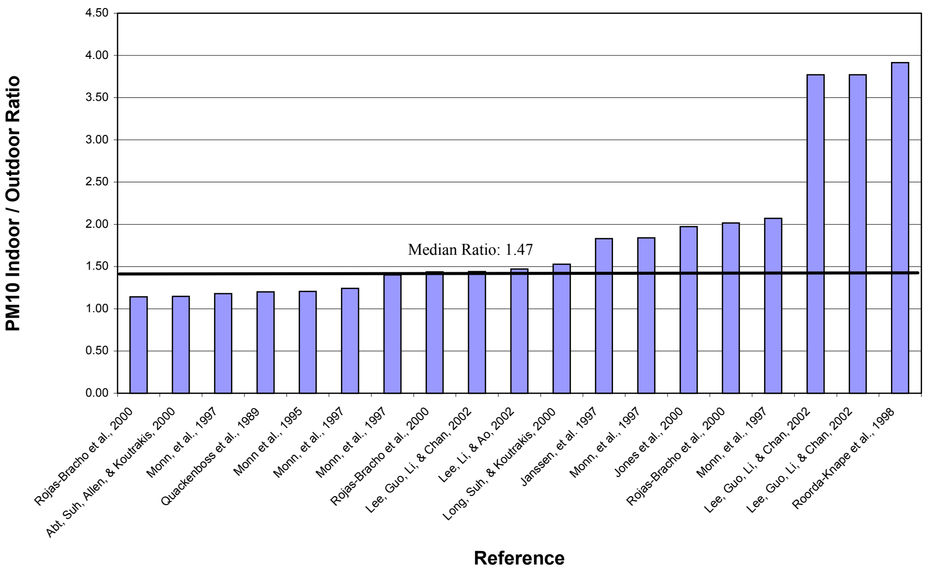

Figure 4 Summary of some reference data of I/O PM_{10} ratio under indoor particle source conditions (Morawska and He, 2003).

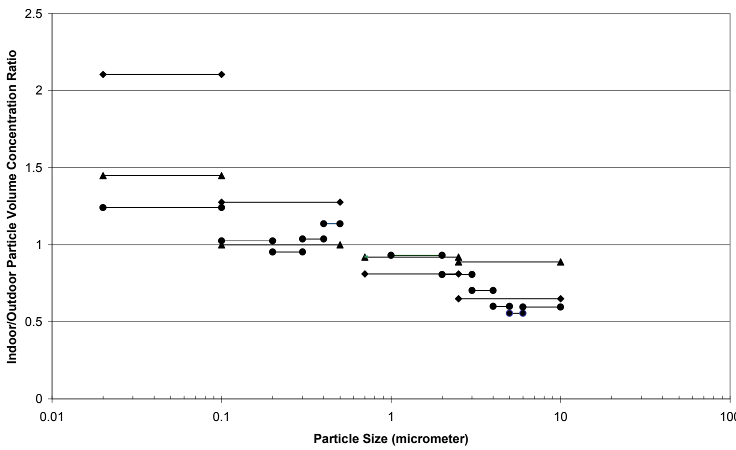

Figure 5 Summary of the reported data on I/O particle number concentration (and volume calculated from the number) in the presence of operating indoor particle sources. ●—Abt *et al.* (2000b); ♦—Abt *et al.* (2000a); ▲—Long *et al.* (2000).

Despite major differences between the studies in terms of use and operation of instruments to measure particle characteristics, a general trend appears to be seen from the data presented in Figure 5. All the reported ratios for concentration of particles smaller than 0.1 µm are well above one. For particles in size above 0.1 and below 2 µm the ratios are either somewhat above or somewhat below one, while for larger particles the reported ratios are in general below one.

CONCLUSIONS

In the absence of operating indoor sources I/O ratios for PM_{10} and $PM_{2.5}$ are consistent between studies. This implies that it can be expected that I/O ratios for a typical indoor environment would be close to the median values reported for all the studies. Therefore, if outdoor concentrations are known and in the absence of indoor sources, indoor concentrations could be predicted reasonably well as well. For particle number concentration and size distribution the scatter of the I/O values is substantial, and therefore more studies in this area should be conducted, before a clearer picture could be developed.

In the presence of operating sources, despite the differences between the environments investigated, most of the reported values of I/O ratios for PM_{10} and $PM_{2.5}$ are below two, with only a few significantly above this value. It is interesting to note that this range of average I/O ratios, while higher than for the cases of no indoor sources, is still relatively narrow, considering the large variation of short-term concentrations of PM_{10} and $PM_{2.5}$ resulting from emissions from the sources, and often increasing temporally by one to two orders of magnitude. While this observation could be useful for conducting assessments of expected indoor/outdoor relationship in the absence of data for a particular environment, it should however be taken with caution, as under certain conditions the impact of indoor sources can be much higher than the general trend. For particle number and size distribution, the trend, which appears to emerge, indicates the significance of indoor combustion sources in the range below 0.1 μm.

REFERENCES

Abt, E., Suh, H., Allen, G. and Koutrakis, P. (2000a). Characterization of indoor particle sources: a study conducted in the metropolitan Boston area. *Environmental Health Perspectives* **108** (1), 35–44.

Abt, E., Suh, H., Catalano, P. and Koutrakis, P. (2000b). Relative contribution of outdoor and indoor particle sources to indoor concentrations. *Environmental Science & Technology* **34** (17), 3579–3587.

Frnack, U., Herbarth, O., Wehner, B., Wiedensohler, A. and Manjarrez, M. (2003). How do the indoor size distributions of airborne submicron and ultrafine particles in the absence of significant indoor sources depend on outdoor distributions? *Indoor Air* **13** (2), 174–181.

Koutrakis, P., Briggs, S.K. and Leaderer, B.P. (1992). Source apportionment of indoor aerosols in SuFFolk and Onondaga Counties, New Yourk. *Environmental Science & Technology* **26**, 521–527.

Lee, H.S., Kang B.-W., Cheong J.-P. and Lee S.-K. (1997). Relationships between indoor and outdoor air quality during the summer season in Korea. *Atmospheric Environment* **31** (11), 1689–1693.

Li, C.-S., Lin, W.-H. and Jenq, F.-T. (1993). Characterization of outdoor submicron particles and selected combustion sources of indoor particles. *Atmospheric Environment* B **27** (4), 413–424.

Long, C.M., Suh, H.H. and Koutrakis, P. (2000). Characterization of indoor particle sources using continuous mass and size monitors. *Journal of the Air & Waste Management Association* **50** (7), 1236–1250.

Long, C.M., Suh, H.H., Catalano, P.J. and Koutrakis, P. (2001). Using time- and size-resolved particulate data to quantify indoor penetration and deposition behavior. *Environmental Science & Technology* **35** (10), 2089–2099.

Monn, C., Fuchs, A., Hoegger, D., Junker, M., Kogelschatz, D., Roth, N. and Wanner, H.-U. (1997). Particulate matter less than 10 mu m (PM sub(10)) and fine particles less than 2.5 mu m (PM sub(2.5)): relationships between indoor, outdoor and personal conc. *Science of the Total Environment* **208** (1–2), 15–21.

Morawska, L. and He, C. (2003). Particle concentration levels and size distribution characteristics in residential and non-industrial workplace environments. In: Morawska, L. and Salthammer, T. (eds), *Indoor Environment, Airborne Particles and Settled Dust*. Weinheim, Germany: WILEY-VCH.

Morawska, L., He, C.R., Hitchins, J., Gilbert, D. and Parappukkaran, S. (2001). The relationship between indoor and outdoor airborne particles in the residential environment. *Atmospheric Environment* **35** (20), 3463–3473.